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# **Big Sky Project**

## **Preliminary Results**

### **June 28, 2017**

Tsubasa Onishi  
Minh C. Nguyen  
Philip Stauffer  
Bill Carey

Los Alamos National Laboratory



EST. 1943

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# Outline

- Recalibration of the Pump Test
- ECLIPSE to NRAP
- Sensitivity Study
- Next Steps

# Calibration of the Pump Test



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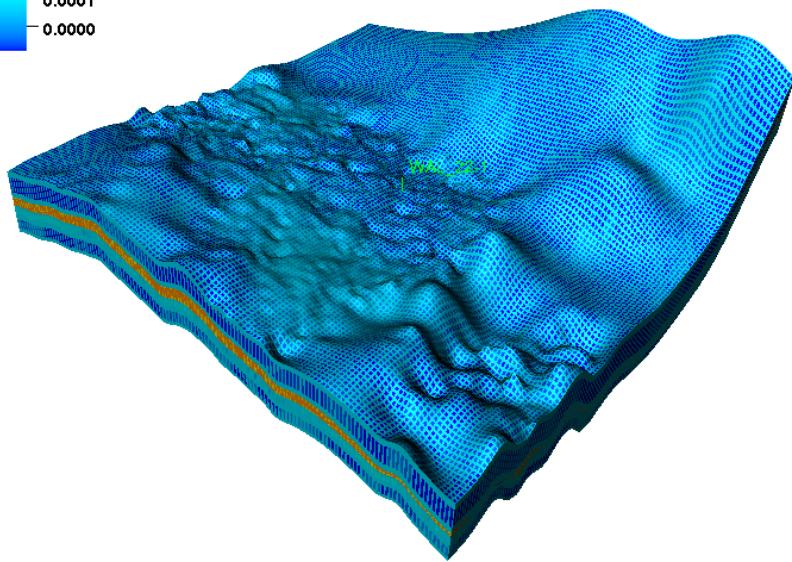
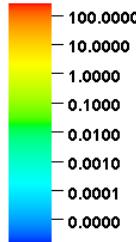
# Background and Objective

## Objective

- Model fractures
- Calibrate the pump test data and update permeability

# Model Setup

Permeability [mD]



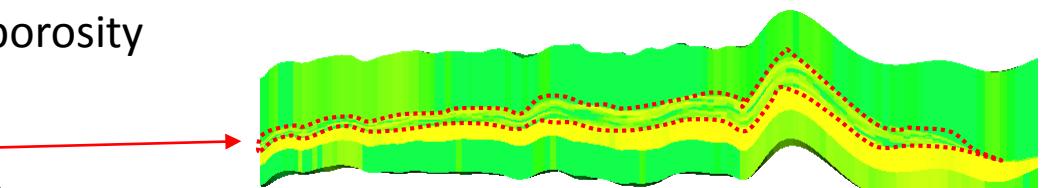
- Dual Porosity Model (Warren and Root, 1963)
- Grid:  $129 \times 129 \times 22$  (#Active cell:366,102)
- Size:  $20,000 \times 20,000 \times 160$  [m<sup>3</sup>]
- Pore volume multiplier at edges (Juanes et al., 2006)
- Isothermal
- 3 Phase (Aqueous, Gaseous, Solid)
- 3 components ( H<sub>2</sub>O, CO<sub>2</sub>, NaCl)
- Van Genuchten relative perm and Pc (LBNL)
- EOS: Modified Redlich-Kwong (Spycher and Pruess, 2005)
- Water injection for 3 days

# Model Parameterization

Parameter	Description	Low	Base	High
PERM_F	Fracture permeability (uniform)	40.0	100.0	160.0
PORO_F	Fracture porosity (uniform)	0.003	0.005	0.007
PERMMULT_M	Matrix permeability multiplier	40.0	70.0	100.0
POROMULT_M	Matrix porosity multiplier	3.0	5.0	7.0
SIGMA	Shape factor	0.012	0.12	0.5

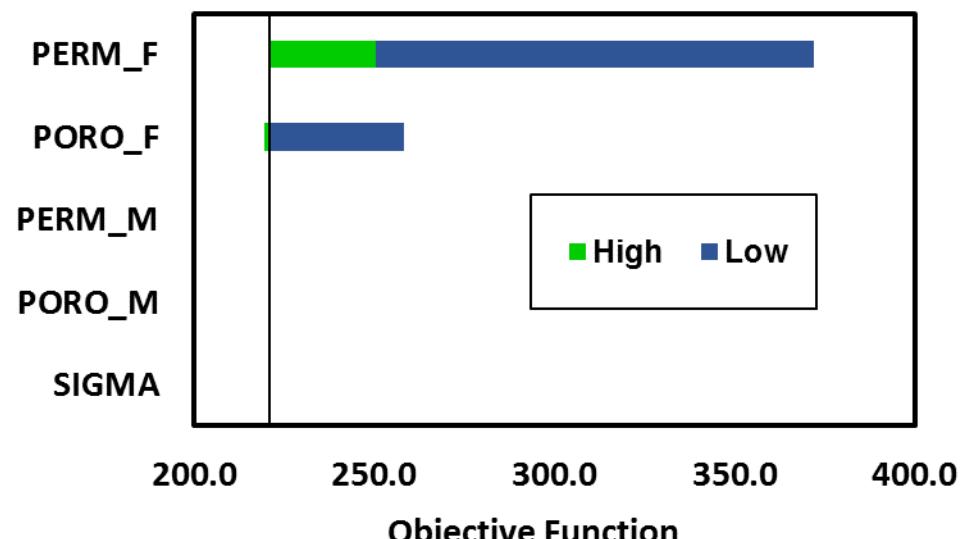
## 5 Calibration Parameters:

- Multiplier to permeability and porosity
- Fracture density
- Focusing on the injection zone
- Ranges are based on the study by LBNL and given data

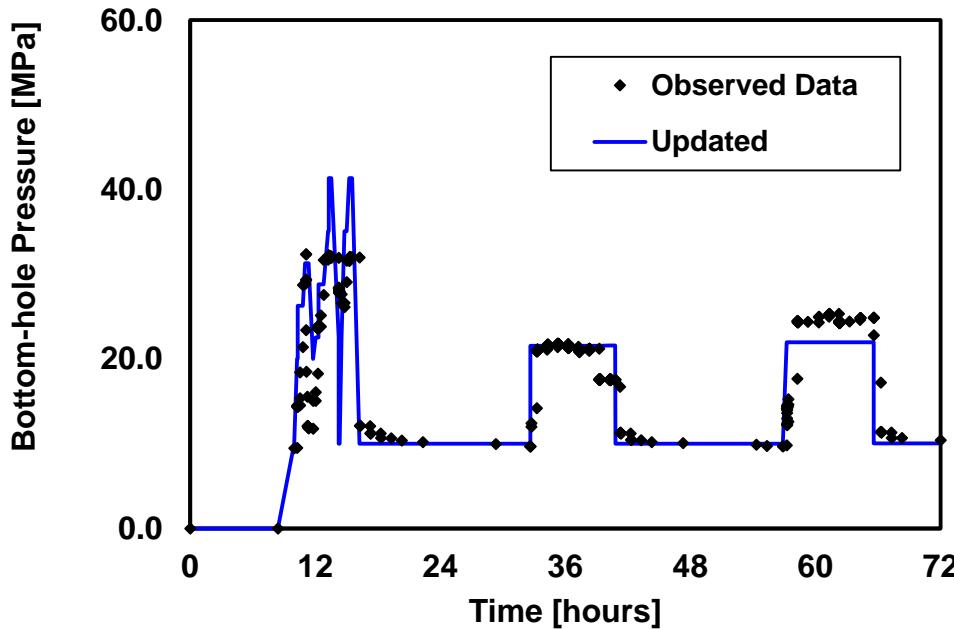


# Sensitivity of Parameters

Parameter	Description	Low	Base	High
PERM_F	Fracture permeability (uniform)	40.0	100.0	160.0
PORO_F	Fracture porosity (uniform)	0.003	0.005	0.007
PERMMULT_M	Matrix permeability multiplier	40.0	70.0	100.0
POROMULT_M	Matrix porosity multiplier	3.0	5.0	7.0
SIGMA	Shape factor	0.012	0.12	0.5



# Bottom-hole Pressure Match



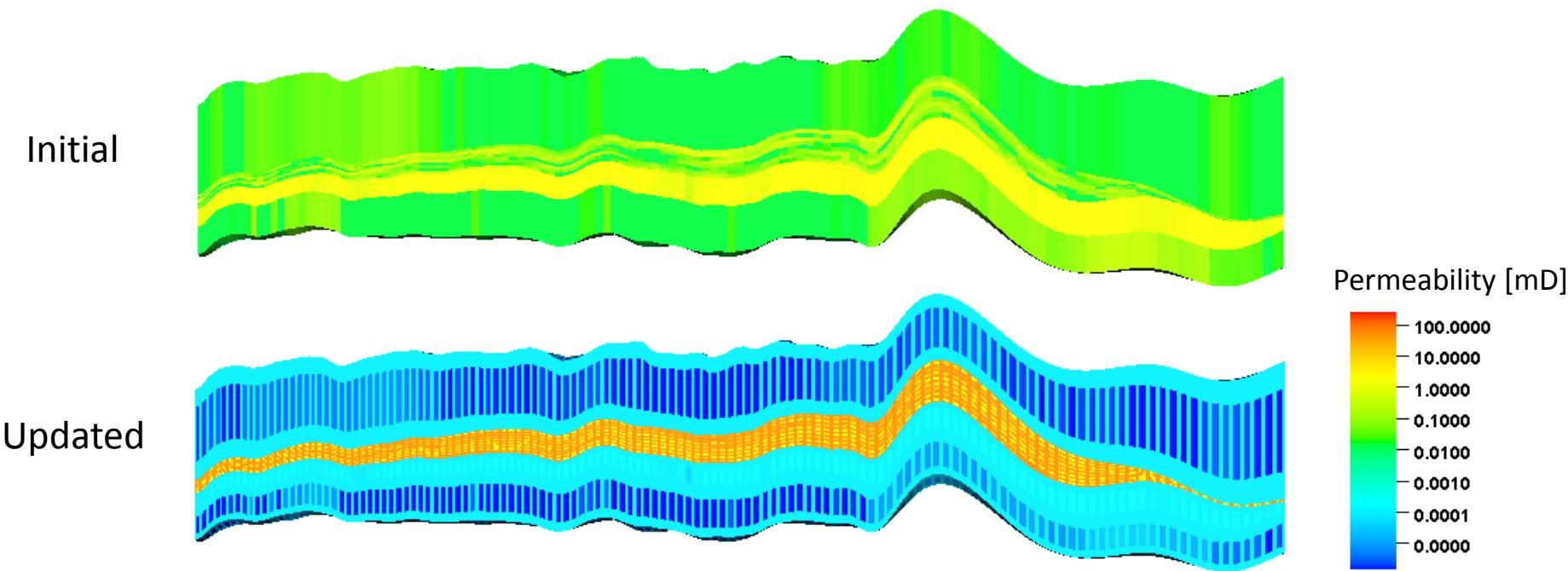
- Manually history matched because:
  - Only well (completed) cells have sensitivities and thus may not be suitable to perform gradient based history matching (e.g., BFGS, Streamline-based, etc.)
  - Limited computational resources to perform stochastic history matching (e.g., GA, PSO, etc.)
- Successfully matched BHP



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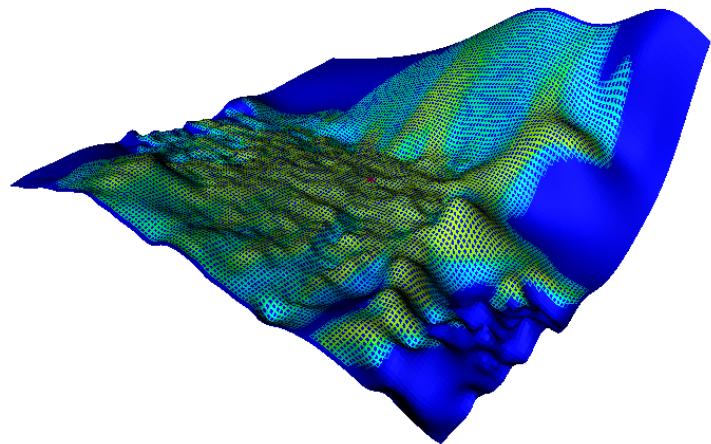
# Initial Model vs Updated Model: Permeability Change



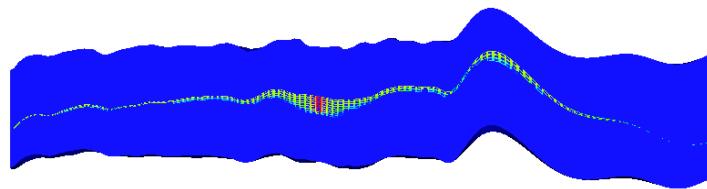
Parameter	LBNL	Updated	Initial
K <sub>m</sub> x, K <sub>m</sub> z [mD]	20.0, 10.0	21.385, 10.693 (mean)	0.30550 (mean)
K <sub>f</sub> [mD]	40.0-100.0	75.0 (uniform for now)	-

$\text{CO}_2$  concentrations at 10 years : 0.25 MT/yr

Layer 2



Cross  
Section



# Summary

- Successful history match
- Calibrated permeability is consistent with the previous study by LBNL
- Fractures are modeled using dual porosity model because uncertainty is too high to model discrete fractures
- The calibrated model allows desired amount of CO<sub>2</sub> injection

# ECLIPSE to NRAP-IAM



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# Background and Objective

## Background

- We have a simulation model ready for CO<sub>2</sub> injections
- RROM-Gen (NRAP tool to convert eclipse output into NRAP-IAM input format) is not capable of dual continuum models (#primary variables is doubled)

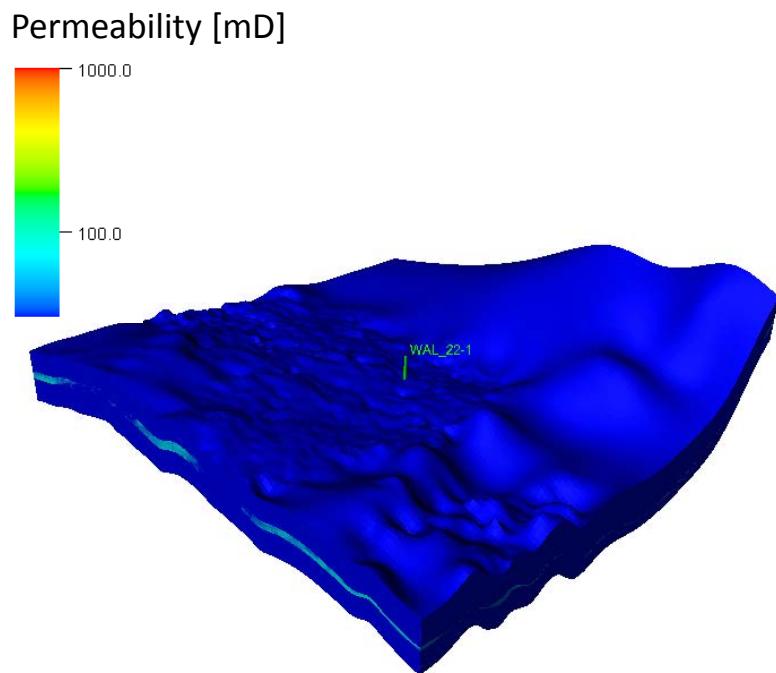
## Objective

- Develop a new RROM-Gen for dual continuum models

# New RROM-Gen: Overview

- Read ECLIPSE outputs
  - Static Data
    - Permeability (Fracture domain)
    - Elevation
  - Dynamic Data
    - Pressure (Fracture domain)
    - Temperature (Fracture domain)
    - Saturation of dissolved CO<sub>2</sub> in aqueous phase (Fracture domain)
    - Supercritical CO<sub>2</sub> saturation (Fracture domain)
- Convert ECLIPSE outputs into NRAP-IAM input format
  - Extract a single layer (high CO<sub>2</sub> concentration)
  - Bilinear interpolation (grid has to be 100 × 100 in NRAP-IAM)

# Application of the RROM-Gen: Kevin Dome Base Case



- Dual Porosity Model (Warren and Root, 1963)
- Grid:  $129 \times 129 \times 22$  (#Active cell:366,102)
- Size:  $20,000 \times 20,000 \times 160$  [ $\text{m}^3$ ]
- Pore volume multiplier at edges (Juanes et al., 2006)
- Isothermal
- 3 Phase (Aqueous, Gaseous, Solid)
- 3 components ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{NaCl}$ )
- Van Genuchten relative perm and  $P_c$  (LBNL)
- EOS: Modified Redlich-Kwong (Spycher and Pruess, 2005)
- BHP < 18.5 [MPa]
- 4.0 years injection

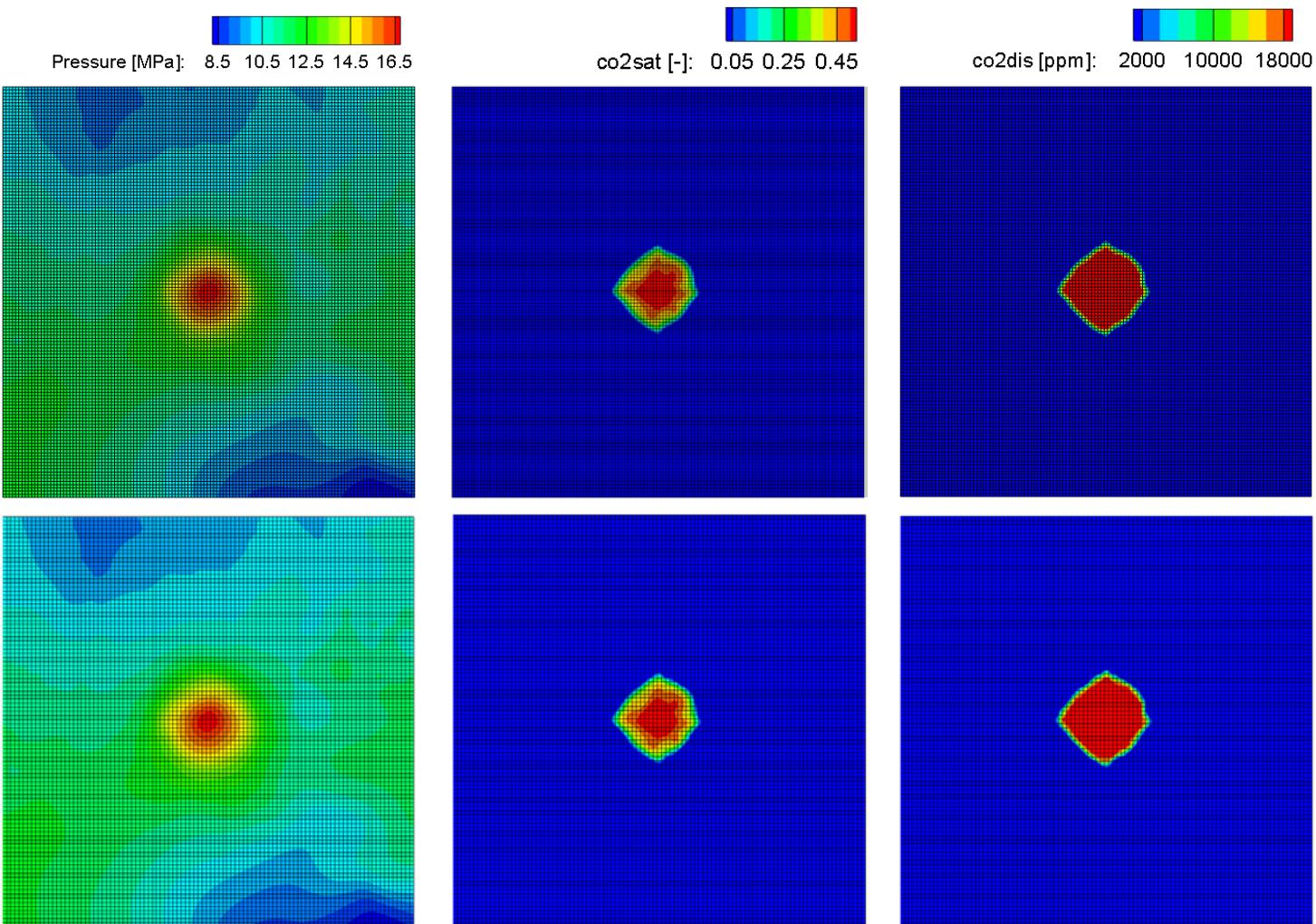


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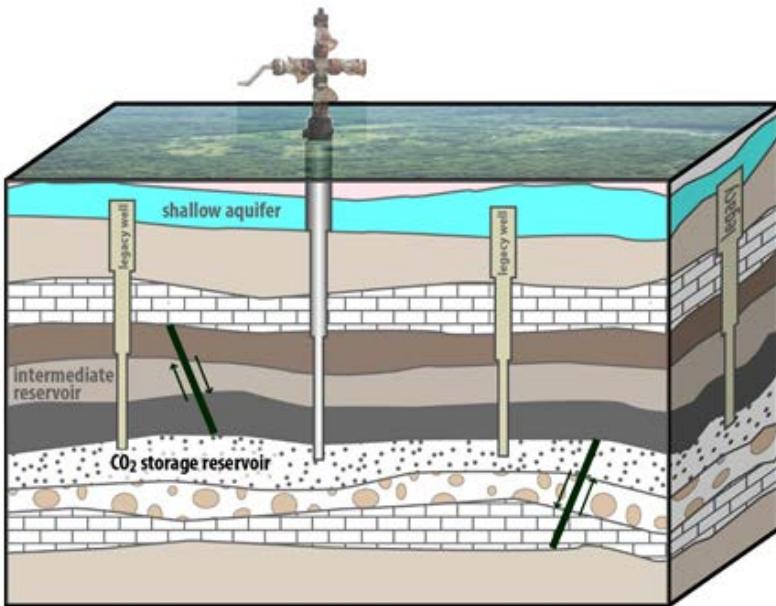
# Validation of the Implementation: Original Grid vs Interpolated Grid

Original Grid  
(129x129)



\*temperature is homogeneous

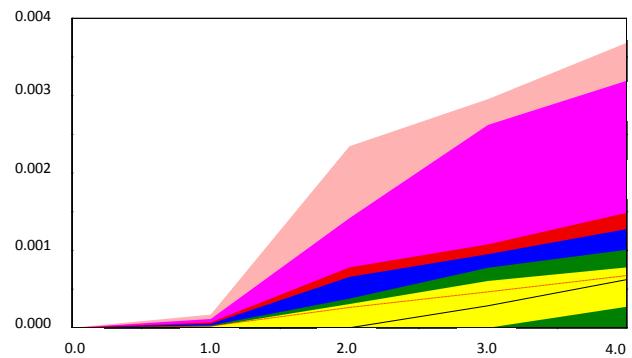
# NRAP-IAM Settings



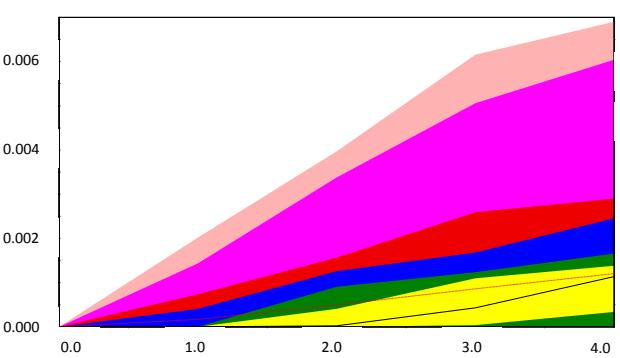
- Scenario: Leakage to ground water through wellbore
- Land surface: Default
- Legacy wells: multiple wells with unknown location
- Shallow aquifer and intermediate reservoir (defaulted)
- Monte-Carlo settings
  - #Realization: 100
  - Latin Hypercube sampling (LHS)

# NRAP-IAM Results: Leakage Rates

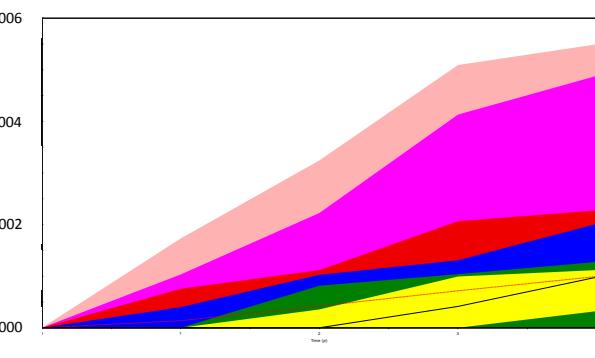
CO<sub>2</sub> leak rate to atmosphere (kg/s)



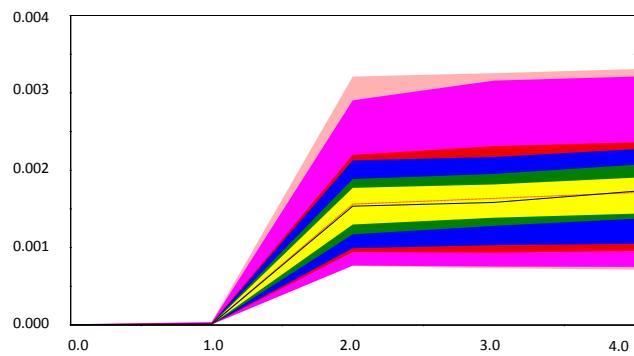
CO<sub>2</sub> leak rate to intermediate aquifer (kg/s)



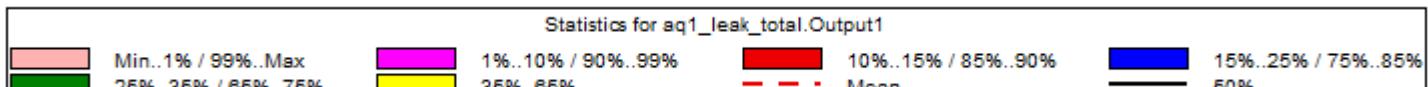
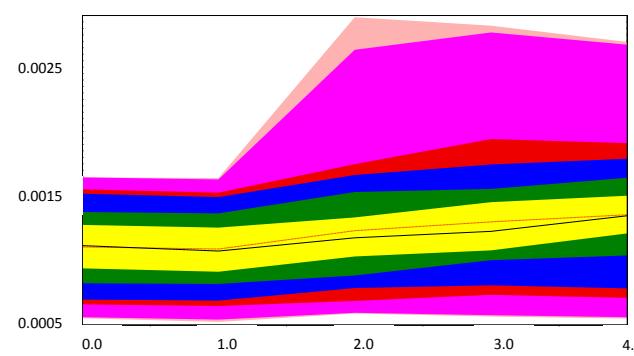
CO<sub>2</sub> leak rate to groundwater aquifer (kg/s)



Brine CO<sub>2</sub> leakage to intermediate aquifer (kg/s)



Brine CO<sub>2</sub> leakage to groundwater aquifer (kg/s)



# Summary

- Developed a new RROM-Gen which is capable of dual continuum models
- The developed RROM-Gen has been validated
- Applied RROM-Gen to the Kevin Dome model base case

# Sensitivity Study



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# Background and Objective

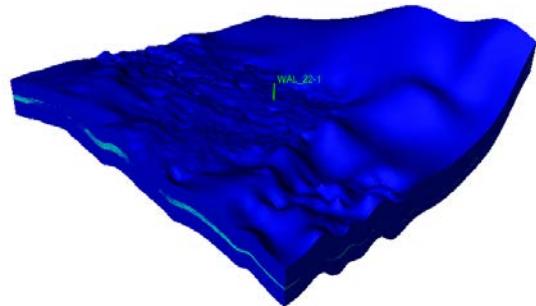
## Background

- We have a simulation model ready for CO<sub>2</sub> injections

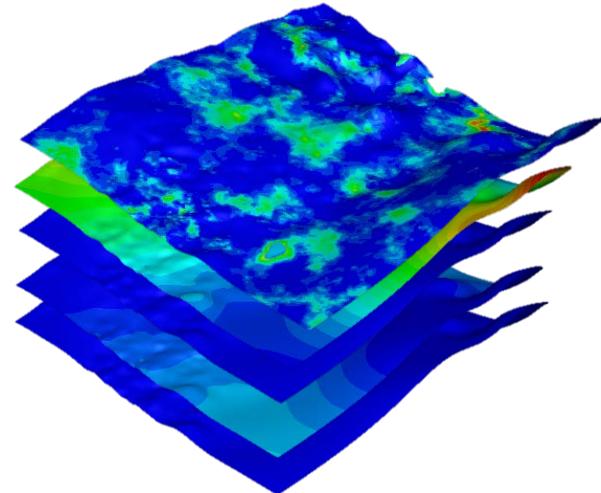
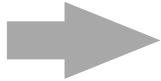
## Objective

- Identify sensitive parameters in terms of leakage risks (Dai et al, 2014 conducted sensitivity studies in terms of CO<sub>2</sub> injection rates, pressure propagation, CO<sub>2</sub> migrations into confining rocks)

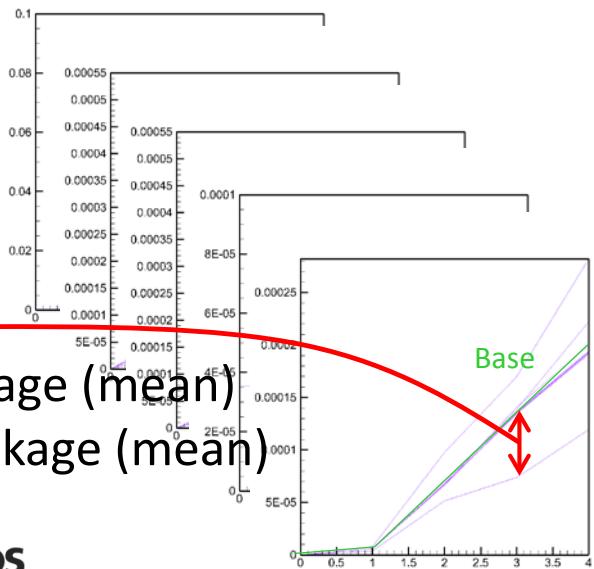
# Approach



Reservoir Simulation

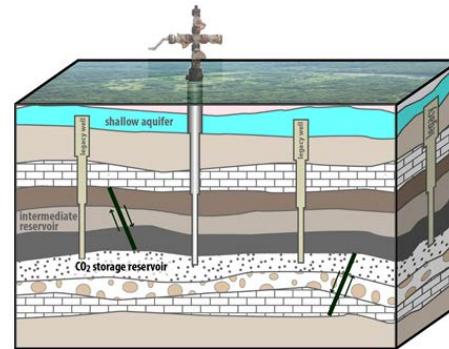
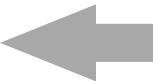


RROM-Gen



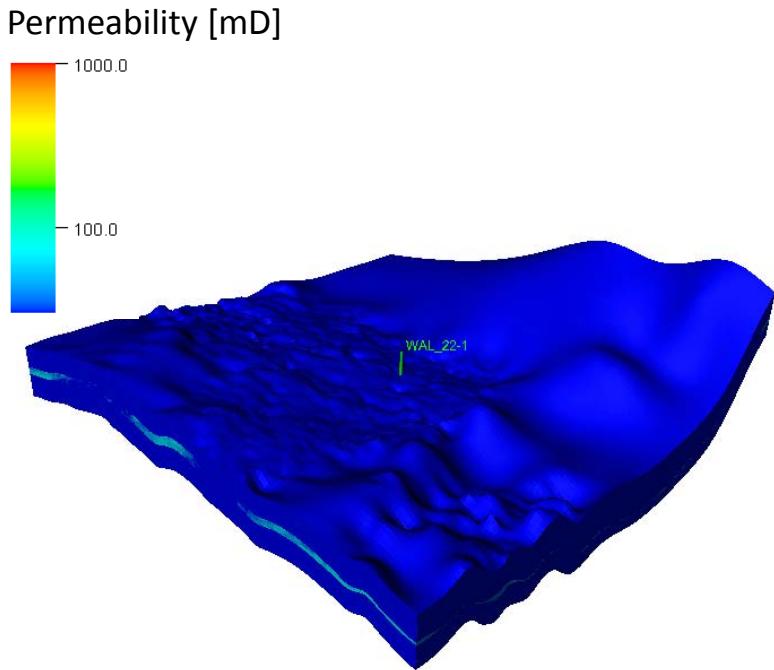
## Sensitivity

- CO<sub>2</sub> leakage (mean)
- Brine leakage (mean)



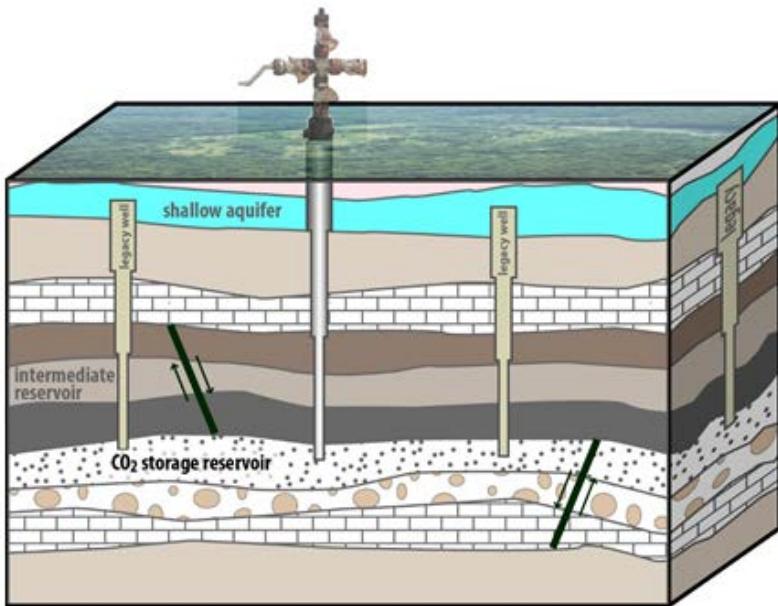
NRAP-IAM

# Model Setup: ECLIPSE



- Dual Porosity Model (Warren and Root, 1963)
- Grid:  $129 \times 129 \times 22$  (#Active cell:366,102)
- Size:  $20,000 \times 20,000 \times 160$  [ $\text{m}^3$ ]
- Pore volume multiplier at edges (Juanes et al., 2006)
- Isothermal
- 3 Phase (Aqueous, Gaseous, Solid)
- 3 components ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{NaCl}$ )
- EOS: Modified Redlich-Kwong (Spycher and Pruess, 2005)
- BHP < 18.5 [MPa] (Dai et al., 2014)
- 4 years injection (Dai et al., 2014)

# Model Setup: NRAP-IAM



- Scenario: Leakage to ground water through wellbore
- Land surface: Default
- Legacy wells: multiple wells with unknown location
- Number of wells
  - mean = 10
  - Std. Deviation 1
  - Min = 5, max = 15
- Shallow aquifer and intermediate reservoir (defaulted)
- Monte-Carlo settings
  - #Realizations = 50
  - Latin Hypercube sampling

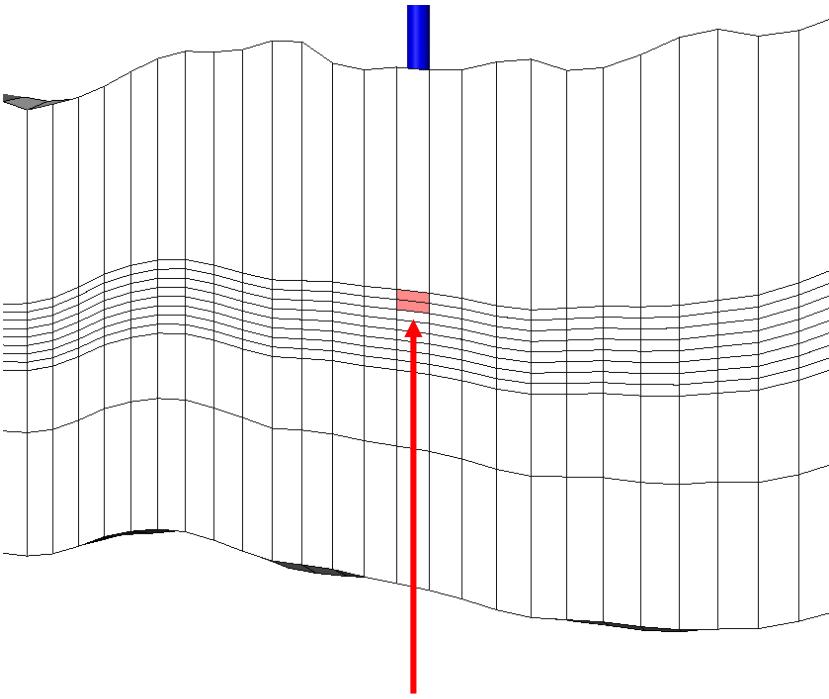
# Model Parameterization

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

**10 Parameters base on Dai, et al 2014, Pruess and Garcia, 2002 Eigestand et al., 2009 and others**

- Permeability multiplier
- Relative permeability
- Capillary pressures
- Shape factor
- Salinity of the aquifer

# Model Parameterization: Kf\_Range



- Range in variograms
- Sequential Gaussian Simulation using SGEMS
- Perm range is based on SLB FMI analysis
- Focusing on injection zone
- Porosity is estimated based on Dai et al ., 2014 and Bernabe et al, 2003 to reduce number of parameters
  - Constants (a and b) are tuned to be consistent with the pump test history matching results

$$k = a\phi^b$$

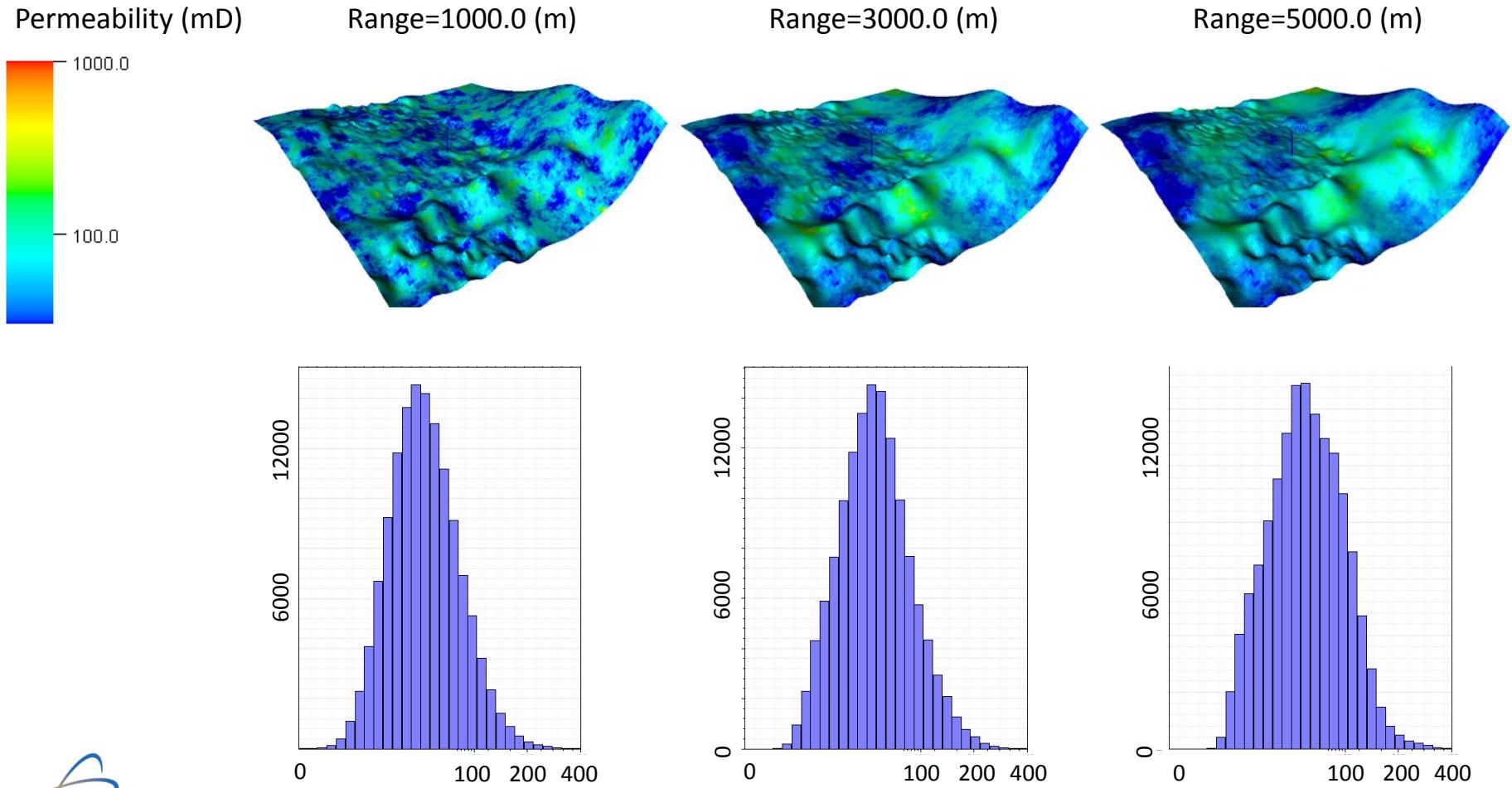
Hard data: non zero  $\frac{\partial \phi(k)}{\partial k}$  in the pump test history matching (Perm $\sim$ 60.0 mD)



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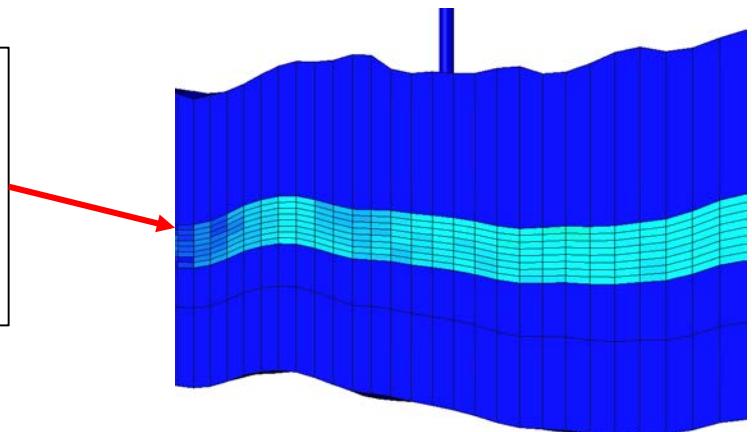
# Model Parameterization: Kf\_Range



# Model Parameterization: KvKh

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

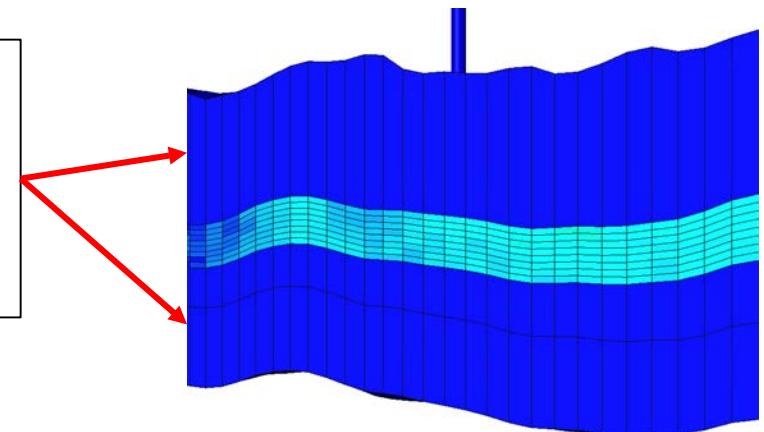
- Vertical fracture permeability anisotropy at injection zone
- Range is based on (Dai et al., 2014)
- KvKh at confining rocks are based on the LBNL study and fixed for simplicity



# Model Parameterization: Km\_ConfRock

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

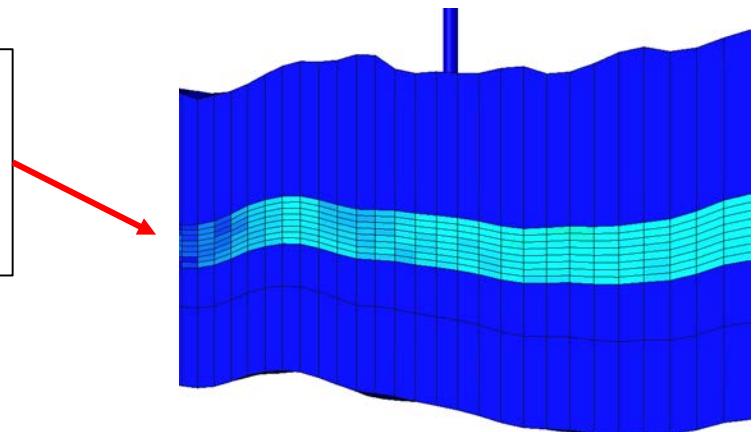
- Same permeability is used in Upper Duperow and Lower Duperow (Permeability and porosity are similar in the caprock and the basement (Dai et al., 2014))
- Range is based on (Dai et al., 2014)



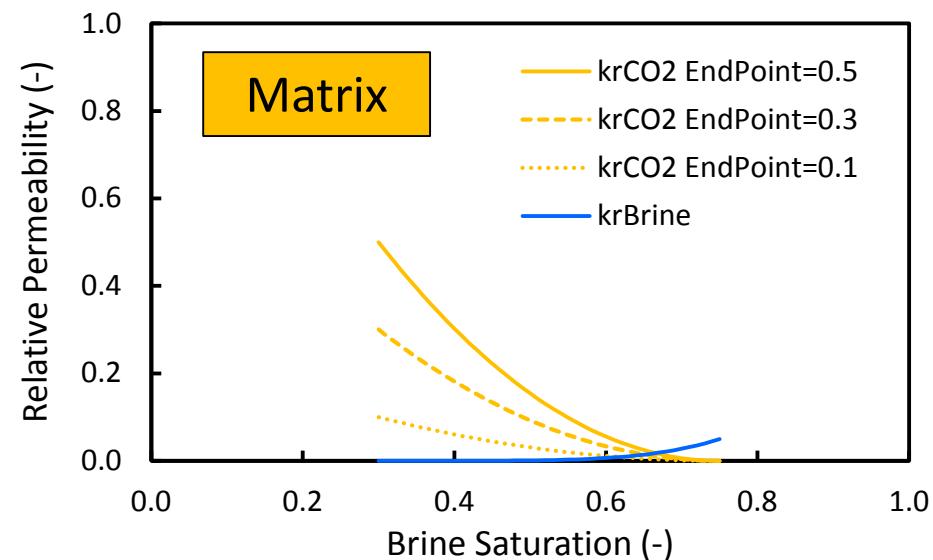
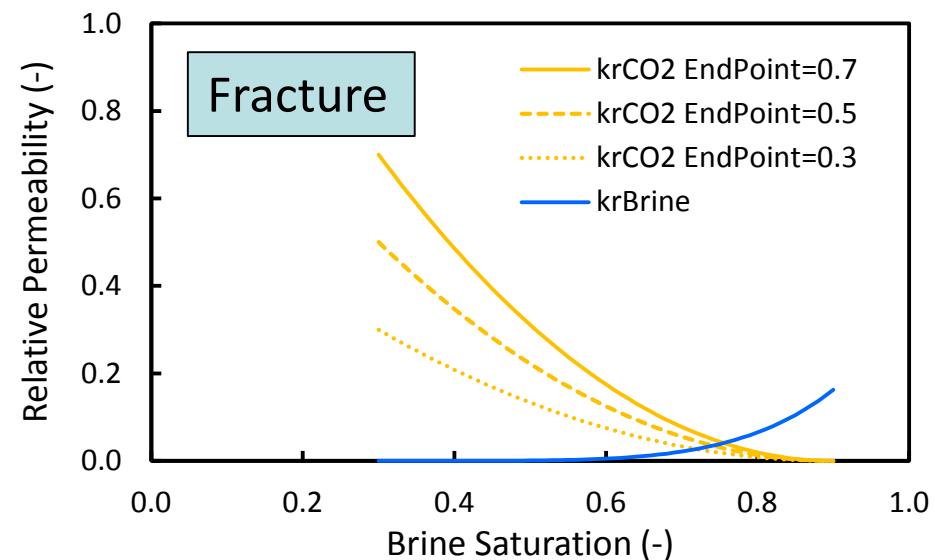
# Model Parameterization: Km

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

- Matrix permeability at injection zone
- Matrix permeability at confining rocks are based on the LBNL study and fixed
- Range is based on the LBNL study



# Model Parameterization: KrCO2f\_End & KrCO2m\_End

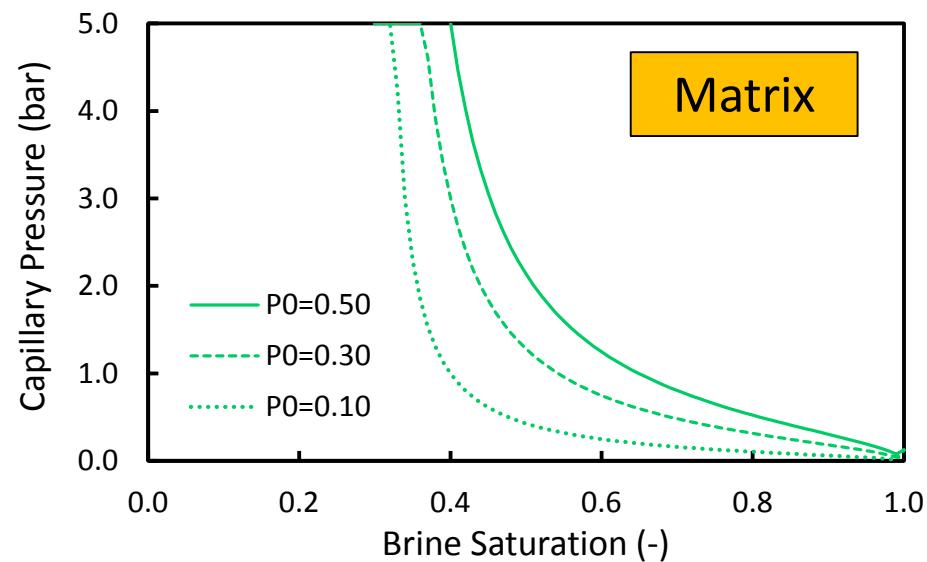
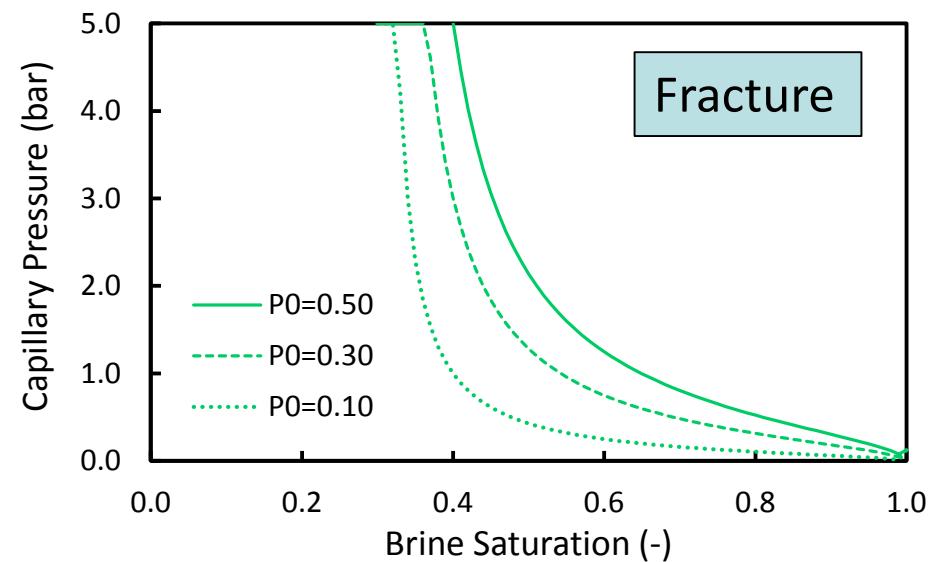


- End point of CO<sub>2</sub> relative permeability based on (Yoshida et al., 2016)
- Brine relative permeabilities are based on the LBNL study and fixed
- Corey equation (Lake, 2010)

$$k_{r,CO_2} = k_{r,CO_2}^0 \left( \frac{S_{CO_2} - S_{CO_2,ir}}{1 - S_{CO_2,ir} - S_{brine,ir}} \right)^m$$

$$k_{r,brine} = k_{r,brine}^0 \left( \frac{S_{brine} - S_{brine,ir}}{1 - S_{CO_2,ir} - S_{brine,ir}} \right)^n$$

# Model Parameterization: Pcf & Pcm



- Strength coefficient of capillary pressure in fracture and matrix based on (Pruess and Garcia, 2002, Yoshida et al., 2016 and others)
- Van Genuchten function (Van Genuchten 1980 and Pruess and Garcia, 2002)

$$P_c = P_0 \left[ \left( S^* \right)^{-\frac{1}{\lambda}} - 1 \right]^{1-\lambda}$$

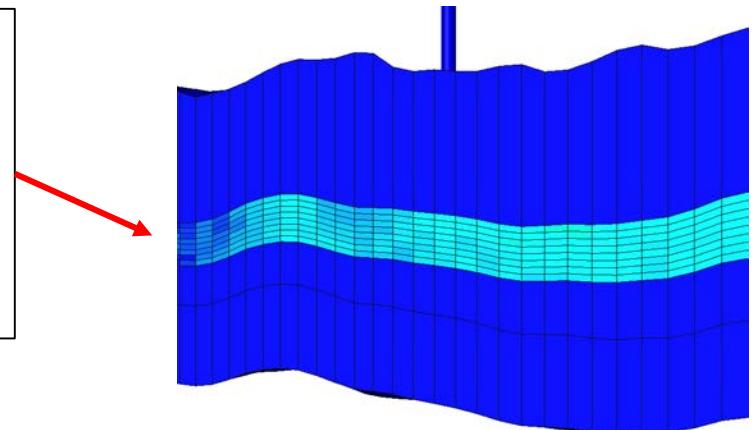
Strength Coefficient

$$S^* = \frac{S_{brine} - S_{brine,ir}}{1 - S_{brine,ir}}$$

# Model Parameterization: Sigma

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

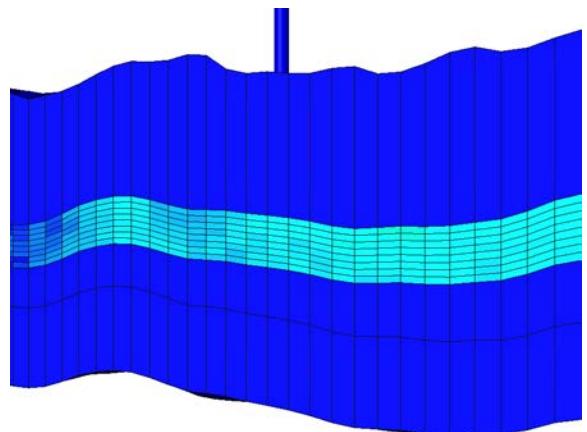
- Shape factor (fracture density)
 
$$F_s = 4 \left( \frac{1}{l_x} + \frac{1}{l_y} + \frac{1}{l_z} \right)$$
- Based on (lino et al., 2016) for now
- Range is uncertain



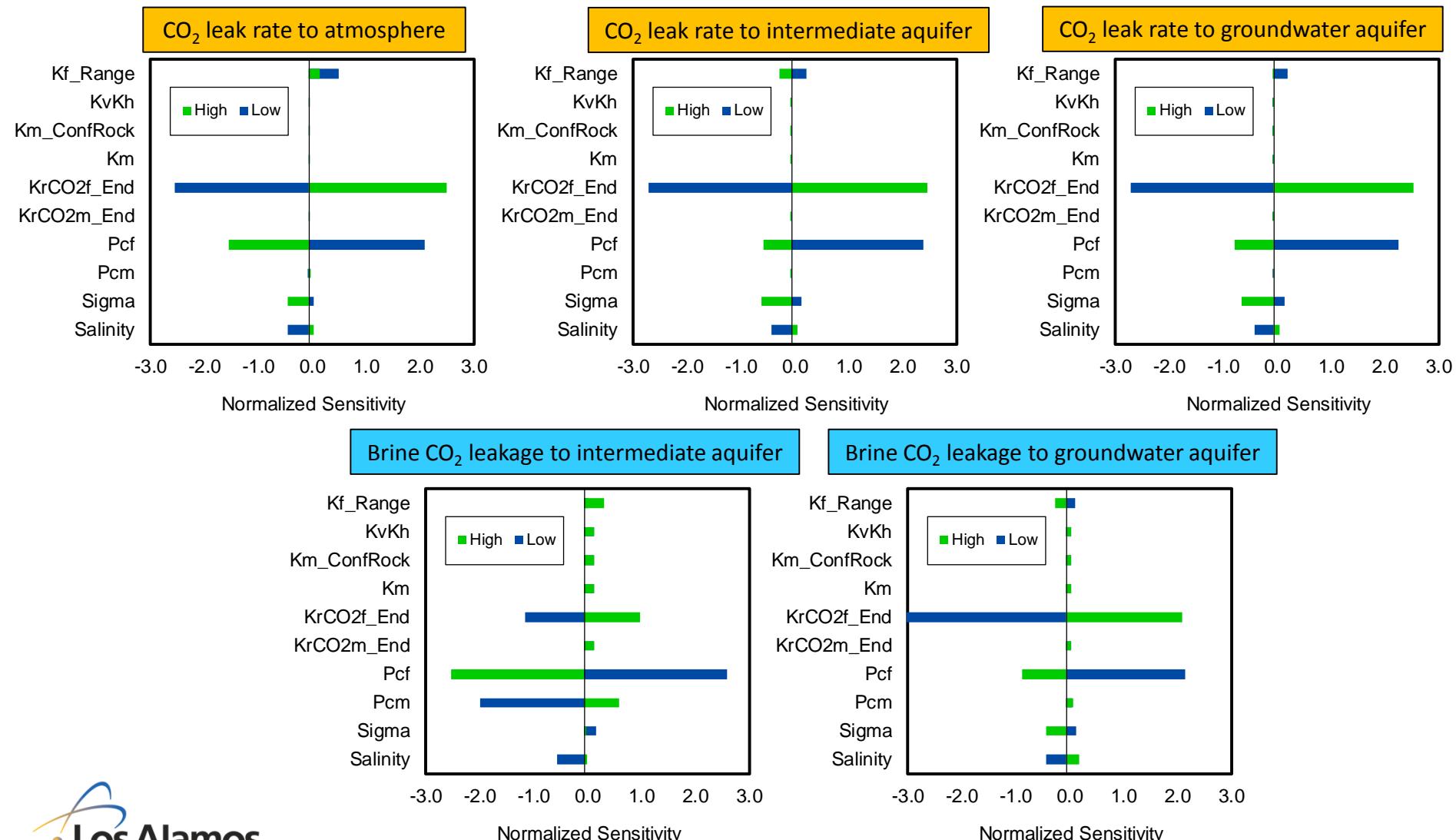
# Model Parameterization: Salinity

Parameter	Description	Low	Base	High
Kf_Range	Range of variogram (m)	1000.0	3000.0	5000.0
KvKh	Vertical permeability anisotropy ratio (-)	0.02	0.5	1
Km_ConfRock	Permeability of caprock and basement (mD)	0.0003	0.03	3.0
Km	Matrix perm (mD)	10.0	30.0	50.0
KrCO2f_End	End point CO <sub>2</sub> relative permeability in fracture (-)	0.3	0.5	0.7
KrCO2m_End	End point CO <sub>2</sub> relative permeability in matrix (-)	0.1	0.3	0.5
Pcf	Strength coefficient of capillary pressure in fracture (bar)	0.1	0.3	0.5
Pcm	Strength coefficient of capillary pressure in matrix (bar)	0.1	0.3	0.5
Sigma	Shape factor (m <sup>-2</sup> )	0.12	1.2	5.0
Salinity	Salinity of the aquifer (ppm)	10,000.0	20,000.0	30,000.0

- Salinity of the aquifer
- Salinity is greater than 20,000 ppm (NETL)



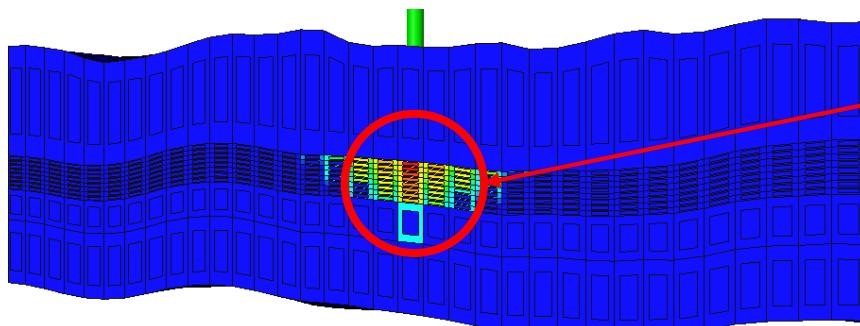
# Sensitivity of Parameters



# Sensitivity: Summary

- Heavy hitters:
  - Fracture end point relative permeability of CO<sub>2</sub> (consistent with Yoshida et al., 2016)
  - Capillary pressures

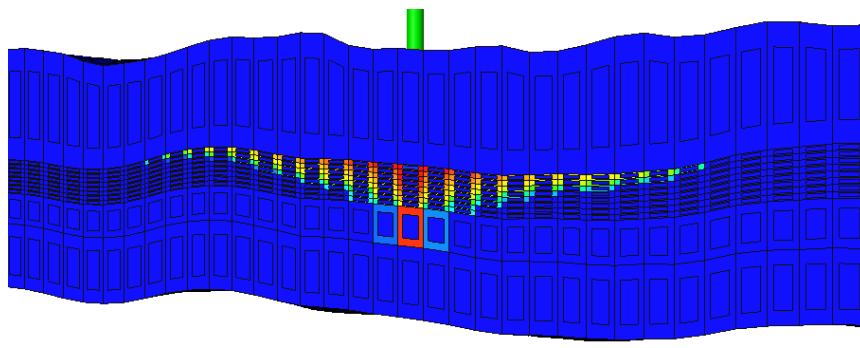
High Pcf



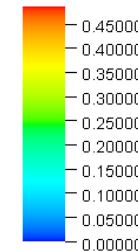
More fracture-matrix flow

Consistent with transfer functions  
(Warren and Root, 1963)

Low Pcf



Gas Saturation (-)



# Next Steps

- Probability distribution and sampling (LHS) for heavy hitters
- Prepare low, base, and high for the other parameters
- Include post injection period
  - Some parameters can be significant
- Other parameters
  - Pore volume at edge aquifer
  - Include FMI data as hard data for SGS
  - Grid resolution (LGR) ... Modifications of the RROM-Gen are required
  - Hysteresis (Juanes et al, 2006) ... may be significant during post injection period
- Include legacy well quality and locations in NRAP-IAM



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